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The Hydrid Transmission

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ABSTRACT

The Floating Cup principle strongly increases the efficiency of hydraulic pumps, motors and transformers. Recent tests have proven an efficiency of up to 98%. For automobiles and other vehicles, this opens the opportunity for the ‘Hydrid’: a full hydraulic hybrid transmission between engine and wheels. The Hydrid has in-wheel hydraulic motors, hydraulic transformers for variable traction control and a common pressure rail including accumulators for power management and energy recuperation. The Hydrid offers the same advantages as hybrid electric drive trains, but without the cost penalty.

AVOIDING DOUBLE TROUBLE

Hybrid electric vehicles are compromises. The pure mechanical transmission (Figure 1) is unparalleled when it comes to cost, weight and efficiency. On the other hand, gear transmissions and even CVT’s lack flexibility regarding energy management, energy transformation and energy storage. Electric systems are in this respect much more convenient, but the power density and the efficiency are too poor to make a full electric drive feasible. For that reason a compromise has been found in creating mixed or so-called hybrid configurations of mechanical and electric drive trains.

However, if a flexible, non-mechanical transmission principle could be found which would have the same performance, cost and efficiency as the existing mechanical transmissions, there would be no reason for this mixed ‘double trouble’ hybrid configuration. In this article, a full hydrostatic all-wheel drive train is proposed, which eliminates the complete mechanical drive train between the engine and the wheels. Figure 2 shows the main components of this hydraulic hybrid transmission, in this paper further referred to as the ‘Hydrid’ [1].

In the Hydrid, all wheels have an in-wheel hydraulic unit. The units have a constant displacement and can operate in 4 quadrants (both forward and reverse, in propulsion and braking mode), which means the units can operate as a motor and a pump. The traction is controlled by means of hydraulic transformers. These transformers are the hydraulic equivalent of a CVT, being able to transform the input pressure and flow to a desired output pressure and flow without principle losses. The transformers can also amplify the pressure, which allows for higher pressure levels delivered to the in-wheel motors, and create a high torque at start-up conditions. The hydraulic transformers are continuously variable. Having two transformers – one for each axle – a completely variable traction control of the front and rear axis is possible. Depending on the vehicular speed, the road conditions and the eventual payload or tow load, the traction can now be optimized for each condition.

The differential function is realized by means of probably the simplest differential that exists in the world: the hydraulic T-joint. As an option, a flow-divider valve can be used to offer a differential lock option.

The hydraulic transformers are connected to a Common Pressure Rail (CPR) having a hydraulic-pneumatic accumulator on the high- and low-pressure side. The accumulators can be sized for power-management only, in which case they only need to have a size of a few liters. As an option, the accumulator size can be increased in order to recuperate part of the brake energy. Hydraulic-pneumatic accumulators can be compared to ultra-capacitors, being able to fulfill much higher power demands than electric batteries. Furthermore they have a high efficiency, a long lifetime and they are not as sensitive to temperature variations as batteries. If needed, electric batteries can be attached to the common pressure rail by means of a generator with a build-in hydraulic motor/pump.

Having a CPR-system with accumulators, the engine is completely separated and isolated from the wheels. The only function of the engine in the Hydrid is to supply energy to the CPR-system in the most efficient and clean way. A small constant displacement pump converts the engine power to hydraulic power. The pump also doubles as a starting motor, thereby facilitating easy stop-and-start operation of the engine, which eliminates the idle-losses. As in other hybrid vehicles, the accumulators allow the engine to be operated in or close to the point with highest efficiency, thereby strongly reducing the part-load losses of engine operation in normal transmission lines.

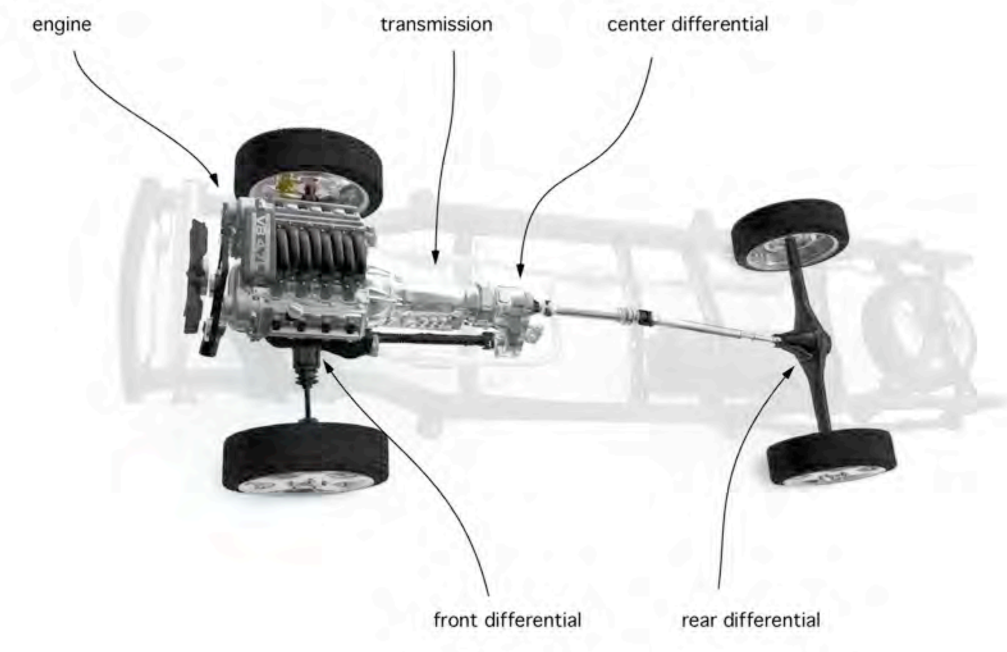

Figure 1: Conventional 4x4 mechanical drive train

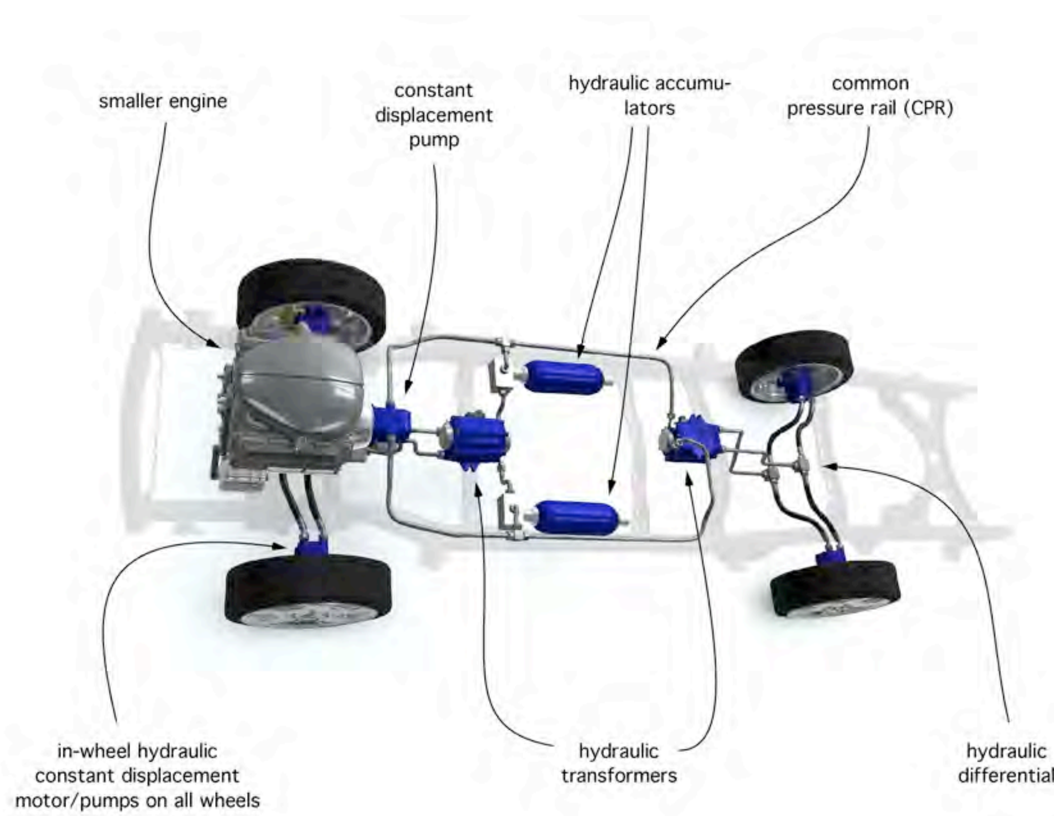

Figure 2: Hydraulic hybrid ('Hydrid') 4x4 drive train

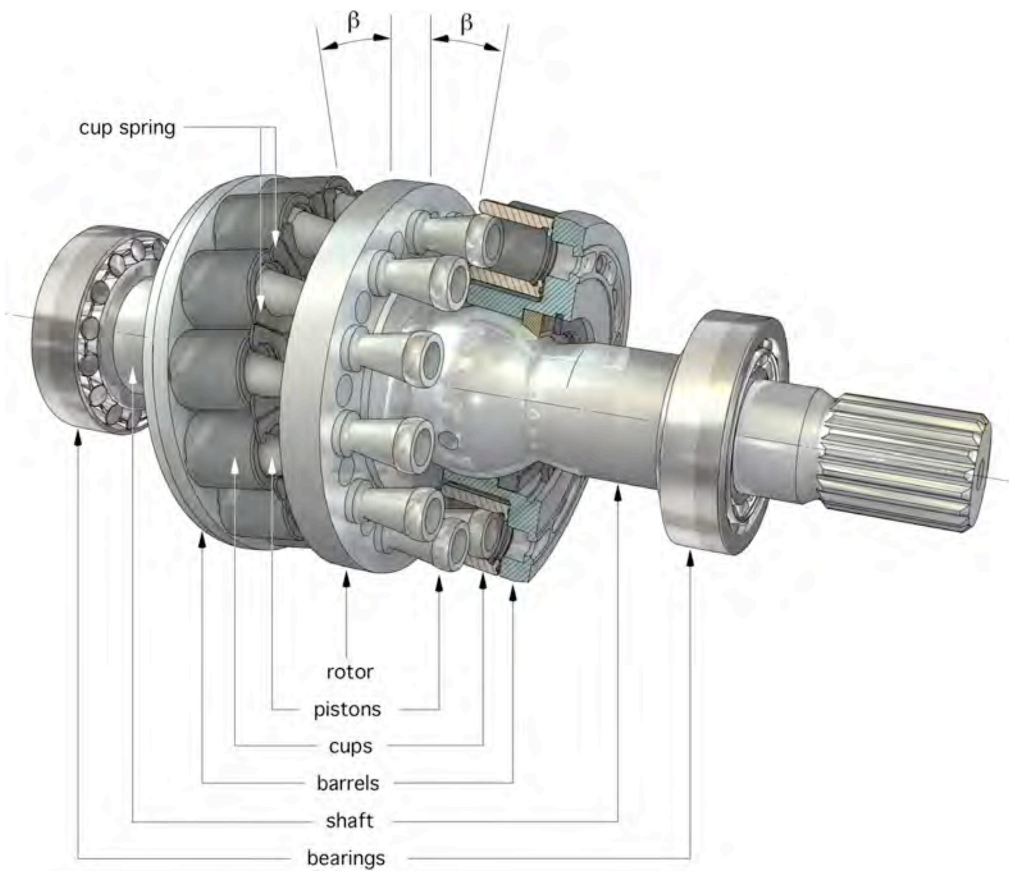

Figure 3. Rotation group of the floating cup pump

THE FLOATING CUP PRINCIPLE

Mechanical transmissions –especially manual transmissions– are efficient and low-cost. According to Lechner [2] a manual transmission has an average efficiency of 92-97%. Kluger [3] measured an average efficiency of 96.2%. (Locked) automatic transmissions and continuously variable transmissions have a lower efficiency, showing average efficiencies of around 85% [3]. All these values are excluding the final gear, the differential and any auxiliaries like power steering. Especially bevel gears can introduce substantial extra torque losses, having a maximum efficiency of around 92% [2]. This is especially of importance for four-wheel and all-wheel mechanical drive trains in which three differentials are being used to split the power across the wheels. Summarized, the total average drive-train efficiency between clutch and wheel varies estimately between 78% for an all-wheel driven vehicle with automatic gearshift, to 90% for a simple manual transmission.

Until recently, hydraulic pumps and motors did not offer an efficiency that could match the high efficiency of gear transmissions. The Floating Cup Principle [4…8] has however dramatically increased the efficiency of hydrostatic machines. Figure 3 shows the main parts of a floating cup pump, excluding the housing and the port plates. The principle is characterized by a large number of pistons, typically around 24, which is about three times as high as in conventional slipper type and bent axis machines. The pistons are arranged in a mirrored, and therefore hydrostatically balanced, double circle configuration. The pistons are press fitted into the rotor. Each of the pistons has its own separate cup-like cylinder, which is floating on and supported by the barrel.

The conversion of mechanical power to hydraulic power (and vice versa) is realized in the direct contact between the oil column in each cylinder and the corresponding piston: there is no sliding interface with a high mechanical load. As a result the floating cup principle has extremely low friction losses [8]. Avoiding the use of piston rings furthermore reduces the friction losses. Instead the pistons are made hollow and expandable when pressurized. The expansion of the piston diameter matches the expansion of the cylinders when they are pressurized, which minimizes the volumetric losses [6].

Figure 4 shows the measured total efficiency of a 28 cc/rev constant displacement machine. The peak total efficiency is 98%. The efficiency diagram also shows the field of operation for the main pump as well as for the in-wheel motors. The main pump is directly connected to the shaft of the engine and delivers its energy directly to the high-pressure accumulator of the CPR-system. Since these accumulators work in a limited pressure range, the pump will always work at a medium to high pressure level and, consequently, at a high efficiency.

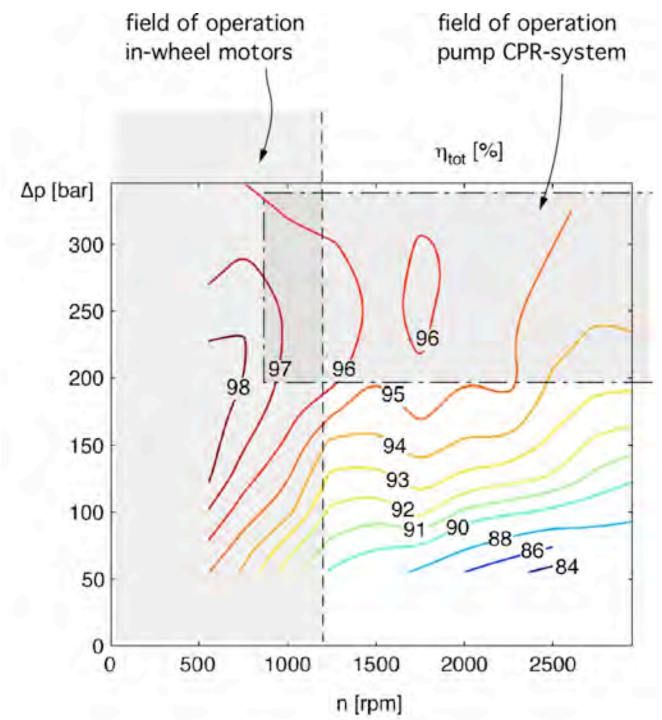

Fig. 4: Measured total efficiency of a floating cup constant displacement pump/motor

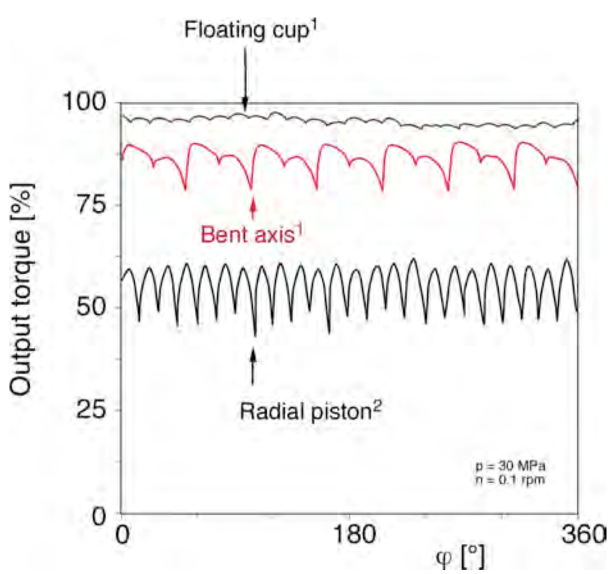

Fig. 5: Break-away torque efficiency measured for three different hydraulic motors ([1] IFAS [8], [2] Parker)

The in-wheel motors are directly connected to the wheels, eliminating the need for a gear transmission. With standard 18” wheels (more specific: 255/70R18) the maximum revolutionary speed of the wheels is around 1200 rpm at a vehicular speed of 180 km/h. Consequently most of the vehicle operation of the in-wheel motors will be at a rotational speed far below 1000 rpm. This is the area where the floating cup principle offers the highest efficiency.

Given that the in-wheel motors determine the traction of the vehicle, it is important to look closely at the torque delivered by these motors at breakaway conditions. Figure 5 shows a comparison of the torque for three different hydraulic motors at a very low rotational speed (0.1 rpm), which is a measure for the starting torque. As can be seen, the floating cup motor has only a few percent friction losses. The floating cup in-wheel motors can therefore remain small and light and will not increase the suspended weight of the original construction with the mechanical drive train. Moreover, due to the much higher number of pistons, the floating cup motor has much less torque variations than the bent axis and the radial piston motors. The higher number of pistons also results in strongly reduced noise and pressure pulsation levels.

Considering the manufacturing cost, most components of the floating cup machines are designed for manufacturing by means of casting, forging, sintering, deep drawing, fine blanking and other automotive production technologies. As a result the specific manufacturing cost per kilogram are expected to get to same level as for engines, gear transmissions and other automotive drive train components (around 10 $/kg [1, 9]).

SECONDARY CONTROL OPTIONS

Hybrid drive trains allow a much more sophisticated energy and power management in vehicles than conventional mechanical drive trains. Energy storage is essential for these systems. For hydraulic hybrid systems this results in the application of accumulators. Having accumulators in the system however breaks the one-to-one relationship between the pump delivery and the motor speed. Therefore it is no longer possible to control the wheel torque and speed on the pump side (the primary side) such as in for instance fork lift trucks, skid steer loaders and many other hydrostatic vehicles. Instead the wheel torque and speed have to be controlled at the motor (or secondary) side. This kind of control is referred to as secondary control [10, 11].

In an all-wheel drive vehicle, having a serial hydraulic hybrid transmission, there are several options for applying secondary control (see figure 6). In the first option (Figure 6a) only the main gear transmission is eliminated; the rest of the mechanical transmission, including all mechanical differentials and drive shafts remains in place.

In the second option (Figure 6b), the mechanical transmission is –as before– only replaced for a part: the complete front and rear axis, including the differentials, are still kept intact. Although only for a two-wheel drive, this is the approach taken in the Volvo Cumulo-drivetrain [12] and (more recently) the HHV-development of the US Environmental Protection Agency (EPA) [9].

It is of course also possible to install a separate secondary controlled variable displacement motor in each wheel (the third option, figure 6c). As in the Hydrid, the mechanical drive train would be eliminated completely. The differential function between the left and right wheels is then however no longer passive, but would require a constant active control of the displacement of all in-wheel motors.

a. One secondary controlled motor driving the center differential

b. Two secondary controlled motors, one for the front differential and one for the rear differential

c. Four secondary controlled motors, one for each wheel

d. Four in-wheel motors having a constant displacement and two (secondary controlled) hydraulic transformers

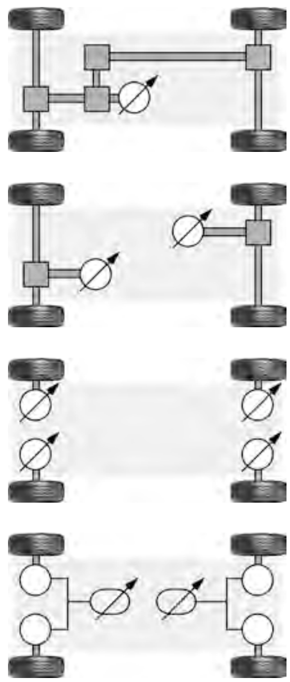

Fig. 6: Secondary control options for hydrostatic transmissions of all-wheel drive vehicles

There are a few disadvantages for secondary controlled in-wheel motors. Variable displacement motors are much heavier than constant displacement motors, especially if they have to be operated in all 4 quadrants, which would substantially increase the suspended weight of the wheel. The weight would further increase if the higher noise level of variable displacement motors has to be reduced by means of insulation. Furthermore, variable displacement motors in general, and secondary controlled motors in particular, are difficult to control at low torque and low speeds (as is required during for instance parking). Finally, variable displacement motors are much more expensive than constant displacement machines.

THE HYDRAULIC TRANSFORMER

In the Hydrid, the secondary control has shifted to the hydraulic transformers (the fourth option, figure 6d). The in-wheel motors can then remain simple constant displacement machines with all the advantages of these machines: low cost, robust, compact, low weight, efficient and silent. Also the differential function can be realized with the T-joint, the simple hydraulic equivalent of the complicated mechanical differential.

Hydraulic transformers are comparable to mechanical constant variable transmissions (CVT's). In a CVT the product of torque and rotational speed remains in principle the same:

$$T_A \cdot \omega_A = T_B \cdot \omega_B \tag{1}$$

Similarly, in a hydraulic transformer, the product of pressure and flow of the input (A-side) is in principle equal to the product of pressure and flow at the output (B-side):

$$p_A \cdot Q_A = p_B \cdot Q_B \tag{2}$$

This way for instance, a small input flow at a high pressure level can be transformed to a larger output flow at a lower pressure level. From the continuity equation it then follows that a third flow always has to be admitted to the hydraulic transformer:

$$Q_T = Q_B - Q_A \tag{3}$$

A hydraulic transformer can be devised by combining a secondary controlled motor/pump with a constant displacement machine (figure 7).

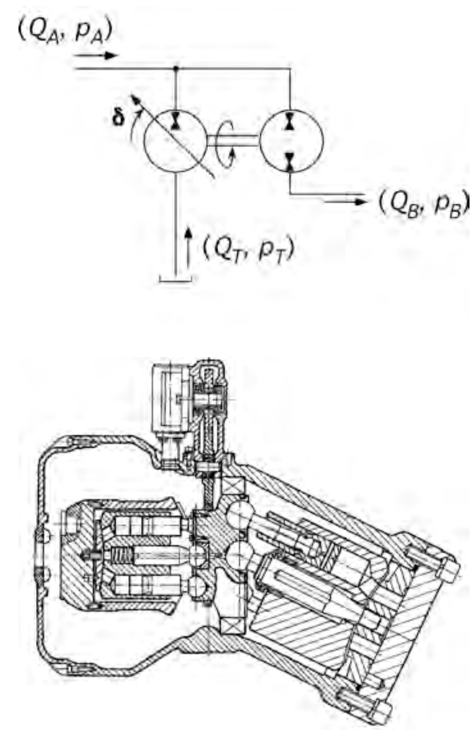

Fig. 7: Conventional hydraulic transformer

A much simpler design of a hydraulic transformer is the Innas Hydraulic Transformer or IHT, which is designed by the Dutch company Innas [13…16]. The design is based on a simple constant displacement machine. The control is realized by:

- adding a third, extra port to the port plate,
- making the port plate free to rotate around its own axis
- controlling the rotational position δ of the port plate with respect to the top dead centre (TDC) of the constant displacement machine.

Figures 8 and 9 show the hydraulic symbol, the port plate definitions and the first design of the IHT, based on a constant displacement bent axis machine.

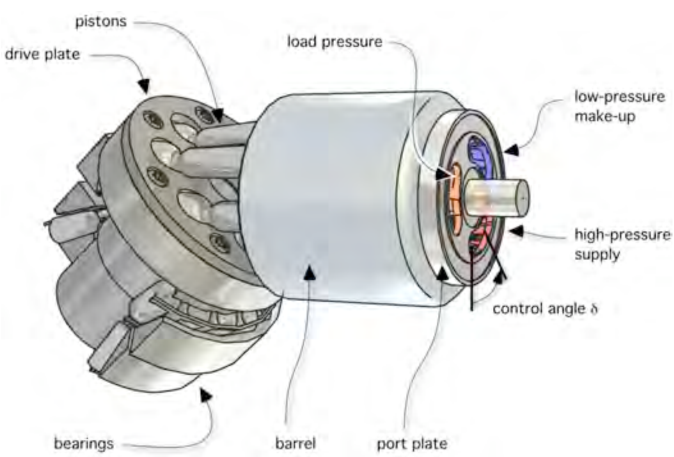

Fig. 8: First prototype of the Innas Hydraulic Transformer (IHT)

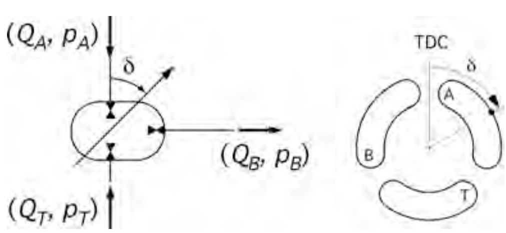

Fig. 9: The hydraulic symbol and the port plate lay-out of the IHT
A = high-pressure side CPR system
B = load side (differential)
T = low-pressure side CPR system
δ = control angle port plate
TDC = top dead center

The control angle δ changes simultaneously the pressure ratio Π between input and output and the flow ratio. In figure 10, the influence of the control angle on the pressure ratio, the maximum flow ratio, and the power ratio is given for a port plate with 3 equally sized ports. In theory, the transformer can create extremely high pressures at the output: at a control angle of 100° the output pressure is almost 3 times as high as at the input. In reality, the maximum pressure will in most cases have to be limited to 500 bar. Assuming a pressure level in the high-pressure accumulator of 350 bar, this would result in a maximum control angle of around 75°.

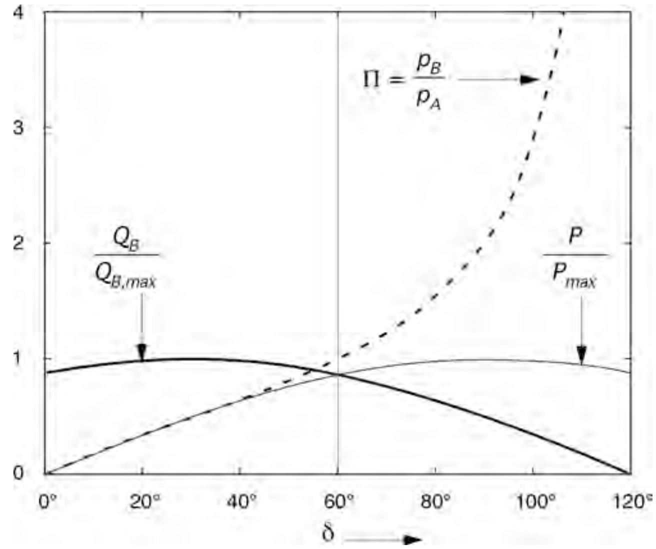

Fig. 10: control characteristics of the Innas Hydraulic Transformer (IHT)

The IHT-concept has already been tested and proven in a forklift truck application, both for the implements (lift cylinders) and for the hydrostatic transmission [17]. The hydrostatic IHT-application was realized in all four quadrants and energy could be recuperated to the accumulators of the CPR-system.

For a continuous operation, also at small control angles and low rotational speeds, it is favorable to have as many pistons as possible. This makes the floating cup principle ideal for the IHT. Figure 11 shows the inner parts of such a floating cup transformer [18].

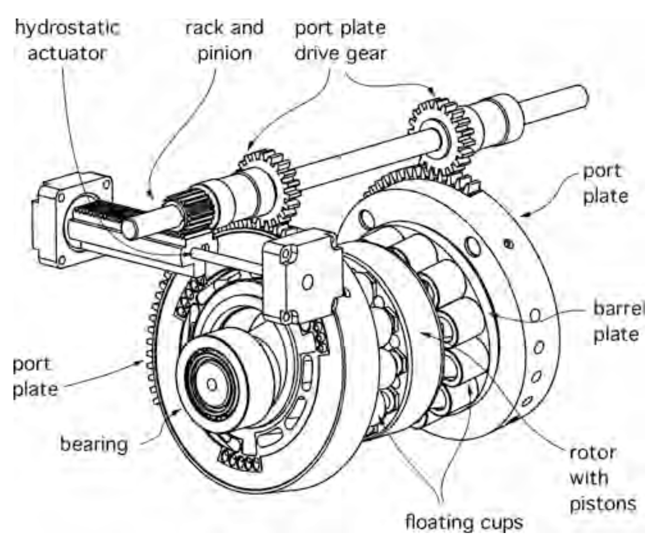

Fig. 11: Innas parts of an IHT based on the floating cup principle.

The efficiency of the IHT is comparable to the efficiency of the FC pump and motor as shown in figure 3. The field of operation of the IHT is however different from the motor and pump operation: the transformer in the Hydrid will run more at high speed and part load conditions than the pump and motor. It is therefore even more important to have low frictional and volumetric losses than for the pump and motors. Having an all wheel drive, it would also be a good option to have one of the two transformers at a neutral position ($\delta = 0°$) at high vehicle speeds and low traction. In that case the full traction of the vehicle has to be delivered by just one transformer, which increases the load and therefore the efficiency of this transformer.

ENERGY STORAGE

The Hydrid is a true hybrid system: power can be delivered by the engine as well as by the accumulators. The first task of the accumulators is to allow a better power management for the main driveline of the vehicle:

- avoiding idle losses of the engine, by means of stopping the engine below a certain minimum power level
- reducing the size of the internal combustion engine, which is possible since the engine no longer determines the maximum traction at the wheels
- increasing the average efficiency of the engine by means of having a smaller engine and letting this engine run at a higher average load.

The accumulators can also be used for recuperation of the kinetic energy of the vehicle during braking. The high efficiency of the accumulators and the floating cup pumps, motors and transformers are advantageous for energy recuperation. Although the energy storage capacity or energy density of hydraulic accumulators is limited, most brake actions do not involve a full stop, but a limited velocity reduction. Also, recently, low weight accumulators have been developed, which weigh only one third of the original accumulators.

Although being a full hydrostatic transmission, this doesn't exclude electric batteries from being applied. Given the high efficiency of the floating cup principle, it is also an option to connect a combination of an electric machine and a floating cup pump/motor to the CPR-system.

POWER PLANT SIZING

The power plant of the hydrid consists of an internal combustion engine (ICE) and a single, constant displacement pump. The pump can also be used as a motor, to facilitate the more frequent start-stop-operation for avoiding idle losses. Motor-operation of the main pump could also be needed for compression braking on the engine, for instance during downhill drives when the accumulators have reached their maximum capacity. In addition a throttle valve in the hydraulic system can be used to dissipate the brake energy if the accumulators (and the optional batteries) are completely charged.

With the constant displacement pump, the limited pressure range of the high-pressure accumulator will result in a corresponding limited torque range of the ICE. Consequently the engine will be driven at a relatively high torque load, which strongly increases the average efficiency of the engine. Instead of a constant displacement pump, it is also possible to apply a variable displacement pump, but this would only result in more part load operation and consequently in a reduction of the energy efficiency of both the engine and the pump.

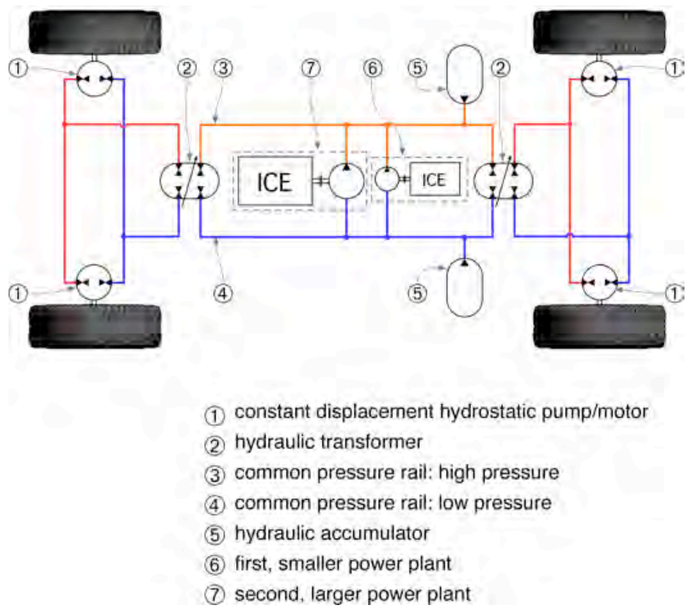

Fig. 12: Hydraulic circuit diagram of the Hydrid having 2 power plants.

A better option would be to have two power plants in a single vehicle, with one engine-pump-combination having a larger capacity than the other (see figure 12). This way the smaller power plant would be used for low power driving conditions, like in-city driving. The larger power plant would for instance be used at highways and interstates, whereas both power plants only have to be used when carrying a high payload and driving it uphill. This way the most extreme operating conditions of the vehicle don't determine the average engine operation.

For all of these options it is important to recognize that in the Hydrid, the engine no longer has a mechanical connection to the wheels. Torque variations created by the engine are not anymore transmitted via the transmission to the wheels. Instead of delivering the torque to the transmission, the engine now drives the pump. Since the pump is directly bolted onto the engine, there is also no more reaction torque on the suspension of the engine-pump-combination.

As a result the effect of the engine on the noise, vibration and harshness (NVH) of the vehicle is strongly reduced. It should therefore be possible to reduce the size and the weight of the flywheel. Furthermore, as in all hybrid vehicles, the engine characteristics can be optimized for the typical field of operation in the hybrid transmission.

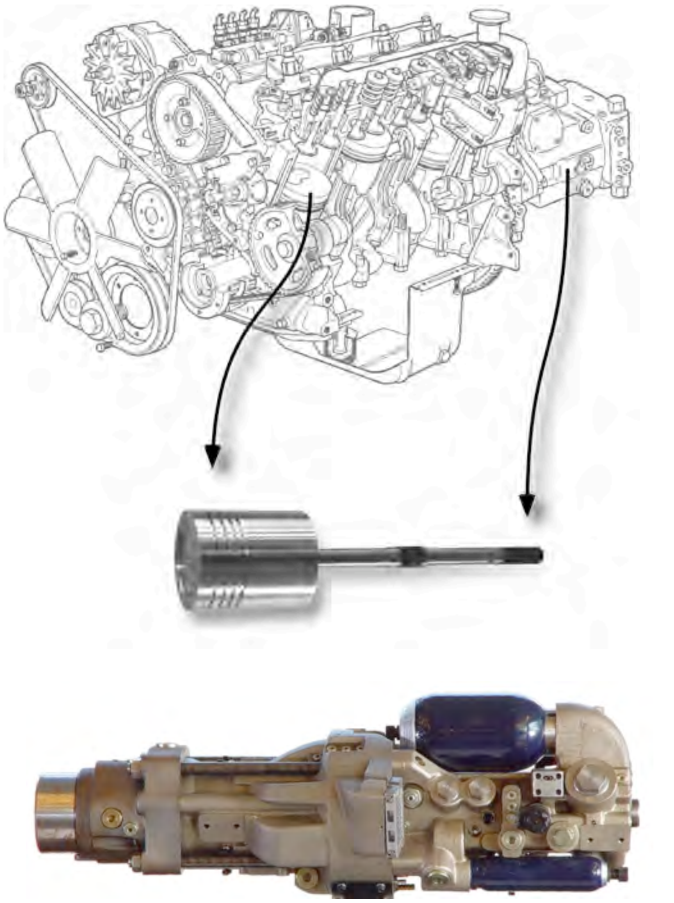

Fig. 13: The free piston (above) and the Chiron hydraulic free piston engine

Finally it is also possible to replace the conventional crankshaft engine by a hydraulic free piston engine (Figure 13). The Chiron free piston engine [19] is especially developed for CPR-systems. In the Chiron, the stroke frequency of the piston is controlled by means of varying the waiting time of the piston in the bottom dead center. This pulse-pause-modulation or PPM allows a continuously variable control of the flow between zero and maximum output flow.

In a hydraulic transmission having accumulators, the engine-pump-combination delivers its hydraulic power in the narrow pressure range defined by the operation of the accumulators. Power transients are therefore predominantly in the flow domain. Consequently, the engine-pump-combination must have a fast response in the flow domain, if possible in the full range between zero and maximum flow. The Chiron free piston engine fulfils this demand, which makes it ideal for the dynamic demands of hybrid vehicles.

CONCLUSION

Hybrid electric vehicles are a major step in reducing fuel consumption and carbon dioxide emissions in the transportation sector. The limited power density and efficiency of electric components however forces a complicated mixed configuration of a mechanical and an electric drive train. As a result hybrid electric drive trains are heavy, complicated and expensive. Even at large scale production the incremental manufacturing cost for a full hybrid electric vehicle are estimated to be between $1800 and $4600, depending on the size of the vehicle [20].

As an alternative, the complete mechanical drive train between the engine and the wheels can be replaced by a full hydrostatic, hybrid transmission. For this, the ensemble of the hydrostatic components must have an efficiency (also at breakaway conditions) that is equal to or even better than the efficiency of the mechanical transmission. The Floating Cup principle could fulfill this demand. This principle also allows the realization of the Innas Hydraulic Transformer, which creates the opportunity for having a simple constant displacement motor in each wheel. Having a separate transformer for the front and the rear axis, the traction between both axis can be divided continuously variable.

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